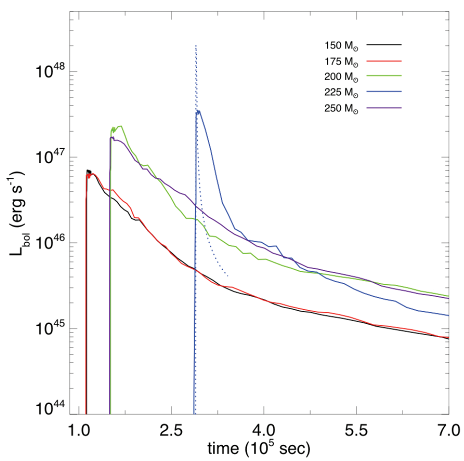
Finding the First Cosmic Explosions

Daniel J. Whalen, T-2, Carnegie Mellon University; Christopher L. Fryer, CCS-2; Lucille H. Frey, Wesley P. Even, XTD-6; Catherine Lovekin, T-2; Aimee L. Hungerford, XTD-6; Christopher J. Fontes, XCP-5; James P. Colgan, T-1

Ten years ago, numerical simulations revealed that the first stars in the universe formed about 200 million years after the Big Bang, ending the cosmic dark ages and beginning the process whereby the universe was gradually transformed from a cold, dark, featureless void into the vast, hot, transparent cosmic web of galaxies we see today. Primordial (or Pop III) stars were also the first great nucleosynthetic engines of the cosmos, creating enormous quantities of the first heavy elements that radically transformed the generations of stars that followed them and making possible the formation of planets and life. Primordial stars are also believed to be one origin for the supermassive black holes that inhabit most massive galaxies today.

Unfortunately, because primordial stars literally lie at the edge of the observable universe, they remain beyond the reach of both current and planned observatories, so not much is known about their properties or the primeval galaxies they populate. Supercomputer simulations suggest that they were very massive, from 30 to 500 solar masses–if so, stellar evolution models indicate that they died in either core collapse supernova explosions or in far more powerful pair-instability supernovae. The latter are thermonuclear explosions that are up to 100 times more energetic than other supernovae and may be visible at great distances. If next-generation instruments such as the James Webb Telescope (JWST) or the Thirty-Meter Telescope (TMT) glimpse these first cosmic explosions they could place the first constraints on the masses of primitive stars and thus the brightness and colors of the protogalaxies they inhabit.

Fig. 1. Bolometric luminosities for 150, 175, 200, 225, and 250 solar-mass pair-instability supernovae at shock breakout. The blue dotted line is the approximate lightcurve obtained by treating the shock as a simple blackbody.



We have used the LANL radiation hydrodynamics code RAGE (Radiation Adaptive Grid Eulerian) to model the first cosmic explosions in the universe and obtain detailed predictions of their light curves and spectra in order to determine if they will be visible to JWST and the TMT. Hydrodynamical profiles from RAGE were then post processed with the extensive LANL OPLIB database of atomic opacities to compute detailed line-absorption features in our spectra–these constitute the chemical "fingerprint" of the explosion. Both core-collapse and pair-instability explosions were simulated to obtain a comprehensive set of primordial (Pop III) supernovae.

Supernova explosions proceed in several stages. Although they begin deep within the star they cannot be seen until they erupt through its surface, a phenomenon known as shock breakout. As we show in Fig. 1, this extremely hot and energetic shock releases a transient pulse of radiation that is more luminous than the entire Milky Way galaxy. It is mostly composed of X-rays and hard ultraviolet (UV) radiation, and it completely ionizes the wind envelope surrounding the star. Earlier models of supernovae explosions, which treat the fireball as a simple blackbody, predict that the duration of the pulse is comparable to the light-crossing time of the star, since photons simultaneously emitted from its poles and its equator would reach an observer at times that differ by the time it takes light to cross the star, as shown by the dotted blue line in Fig. 1. However, our full radiation-transport models show that the breakout photons remain tightly coupled to gas at the surface of the shock and escape into space over an extended period of time. This creates the dimmer but broader breakout pulse shown in Fig. 1.

The fireball cools as it expands, and there is a gradual shift in the spectrum from short wavelengths to longer ones over time, as we show in Fig. 2. As ejecta from the explosion expands into the intergalactic medium it becomes more diluted, and the photosphere of the explosion (the surface from which photons can escape into space) sinks deeper into the ejecta. As it does, heavier elements deep in the debris imprint absorption lines on the radiation spectrum of the explosion. Pair instability supernovae manufacture vast quantities of radioactive nickel, whose decay produces gamma-rays that downscatter in energy as they slowly diffuse out through the massive ejecta. This heats the ejecta and powers the light curve of the explosion after the initial breakout

For more information contact Daniel J. Whalen at dwhalen@lanl.gov

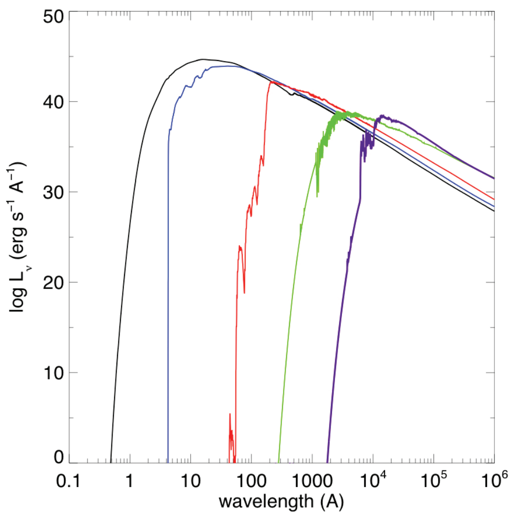


Fig. 2. Evolution of the spectrum of a 250 solar-mass pair-instability supernova. From left to right the times range from 10^4 seconds to three years.

transient. As we show in Fig. 3, the large quantities of nickel synthesized in pair-instability explosions cause them to remain bright for two to three years, in contrast to core-collapse and Type Ia supernovae that fade after a few months. The rebrightening of the explosion that is evident in the more massive explosions at about three months in Fig. 3 occurs when the photosphere of the blast uncovers the hot layer of radioactive nickel deep in the ejecta. The supernova fades after all the nickel has decayed and its photons have diffused out into space.

Radiation from the first supernovae must traverse vast tracts of space over cosmic time to arrive at Earth. Most of the radiation is absorbed by the cosmic web of neutral hydrogen present over most of this epoch, the Lyman-alpha forest. As the universe expanded, the wavelengths of the photons were also stretched to lower energies. Massimo Staivelli, a JWST project leader at the Space Telescope Science Institute, is convolving our Pop III SN spectra with absorption by the Lyman-alpha forest, cosmological redshifting, and JWST NIRCam and NIRSpec filter responses to determine how many of these photons will be captured by JWST. These calculations will reveal out to what redshift (or how far back in time) both JWST and TMT will detect these explosions. If they are discovered at the epoch of first star formation, they will be our first direct probe of the Pop III initial mass function, and hence the character of the first galaxies. Such explosions will also mark the positions of the earliest galaxies in the sky, most of which would otherwise be too dim to be detected. In this and many ways to come, LANL expertise in supernova simulations will open the first direct observational window into the primeval universe.

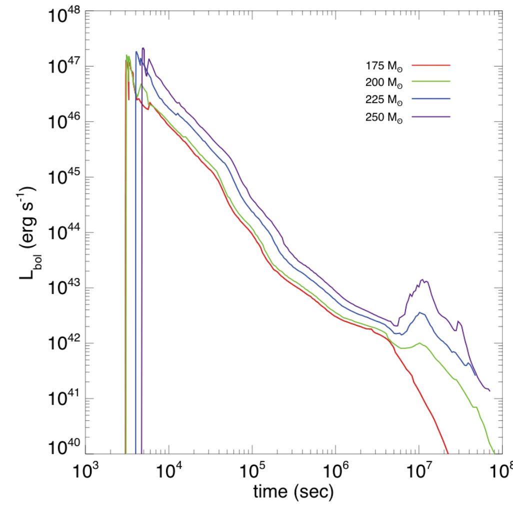


Fig. 3. Bolometric luminosities for 175, 200, 225, and 250 solar-mass pair-instability supernovae out to three years. The resurgence in luminosity at 10^7 seconds in most of the explosions coincides with the descent of the photosphere of the shock into the hot radioactive nickel layer in the ejecta.

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